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ELECTROTHERMAL THRUSTER DIAGNOSTICS

Volume I. Executive Summary

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16. Abstract A flight-qualified electrothermal thruster demonstrated its adaptability to a variety of propellants. Originally qualified for operation with hydrazine propellant, it was operated with nitrogen, hydrogen, and ammonia propellants, demonstrating 73, 61, and 52 percent overall efficiency with these propellants, respectively, when tested over a wide range of operating conditions. By introducing a preheater to admit hot, rather than cold, propellant inlet gases to the thruster's augmentation heat exchanger, delivered specific impulse closer to theoretical performance limits should be achieved.			
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Electrothermal thrusters were successfully developed by a number of investigators in the 1960s and early 1970s (References 1 and 2). Their demonstrated performance compared favorably with earlier theoretical calculations (Reference 3). The first space operation of an electrothermal thruster took place on September 15, 1965 when a 0.042 lbf (0.187 N) resistojet was fired for 30 minutes to adjust the position of a Vela nuclear detection satellite. This device used nitrogen propellant, consumed 90 watts of electrical input power, and operated at a specific impulse of 123 seconds (Reference 4). At present, 20 HiPEHTs (High Performance Electrothermal Hydrazine Thrusters) are operational in space for performing north-south stationkeeping maneuvers on Intelsat V. Sixteen of these thrusters have been fired in space. The HiPEHT is a hybrid device, using chemical energy with electrothermal augmentation to achieve close to 300 seconds I_{sp} (Reference 5).

In examining onboard propulsion requirements for auxiliary propulsion of large platforms, such as Space Station, in low earth orbit, electrothermal thrusters were identified as a near-term technology with growth potential for long-term development (Reference 6). Electrothermal thrusters can be used with various propellants, including storables such as hydrazine and ammonia, with hydrogen, and with those commonly associated with manned systems, such as carbon dioxide and methane. The efflux from these thrusters is generally like the propellants, nonreactive and noncontaminating. Long-term ground tests and space operation have yielded a good data base for pursuing low risk advances in electrothermal technology.

The specific objectives of the project reported herein were to evaluate electrothermal thruster performance limitations that result from materials temperature restrictions, molecular species of exhaust propellant, and propellant/materials interactions. During the technical effort, test data were evaluated for N_2 , H_2 , and NH_3 molecular species. The augmentation heat exchanger from HiPEHT was used as the basic test article, in order to tie the test effort to a data base afforded by existing flight hardware. Earlier work along these lines involved performance characteristics of a vortex heat exchanger with nitrogen, ammonia, methane, and carbon dioxide propellants. Results from the earlier work are discussed in Reference 7, which was primarily directed towards biowaste gas applications.

The test units used during this project were fabricated by modifying the HiPEHT augmentation heat exchanger to accept gaseous, rather than liquid, propellant inlet. Figure 1 is a photograph of an electrothermal test unit. Cold flow and hot firing data were obtained with nitrogen, hydrogen, and ammonia propellants.

Nitrogen performance data are summarized in Figure 2, where specific impulse is shown as a function of power-to-thrust ratio. The solid line on this figure follows the relationship:

$$I_{sp} = 80 + 20 (P/F)$$

where

I_{sp} = specific impulse (sec)

P = IV = electrical input power (watts)

F = thrust (mlbf)

I = heater current (amperes)

V = heater voltage (volts)

Overall efficiency as a function of specific impulse is shown in Figure 3 for five different mass flow rates. Overall efficiency is defined by (Reference 8):

$$\begin{aligned} \eta^* &= 21.8 \times 10^{-3} \frac{FI_{sp}}{P_{in}} \\ &= 21.8 \times 10^{-3} \frac{FI_{sp}}{(IV + \dot{m}h)} \end{aligned}$$

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Figure 1. Electrothermal Test Unit

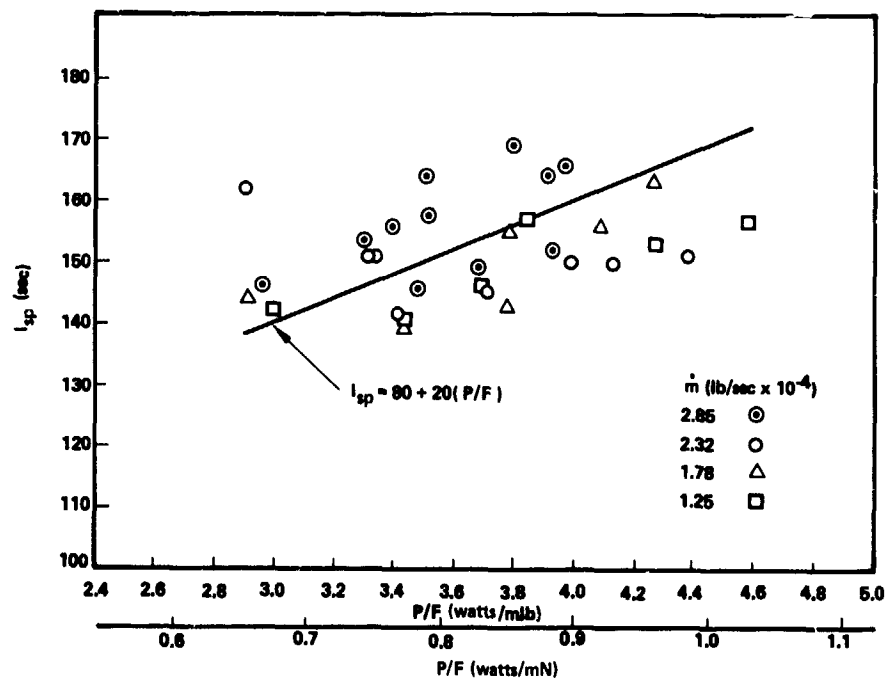


Figure 2. Nitrogen Performance

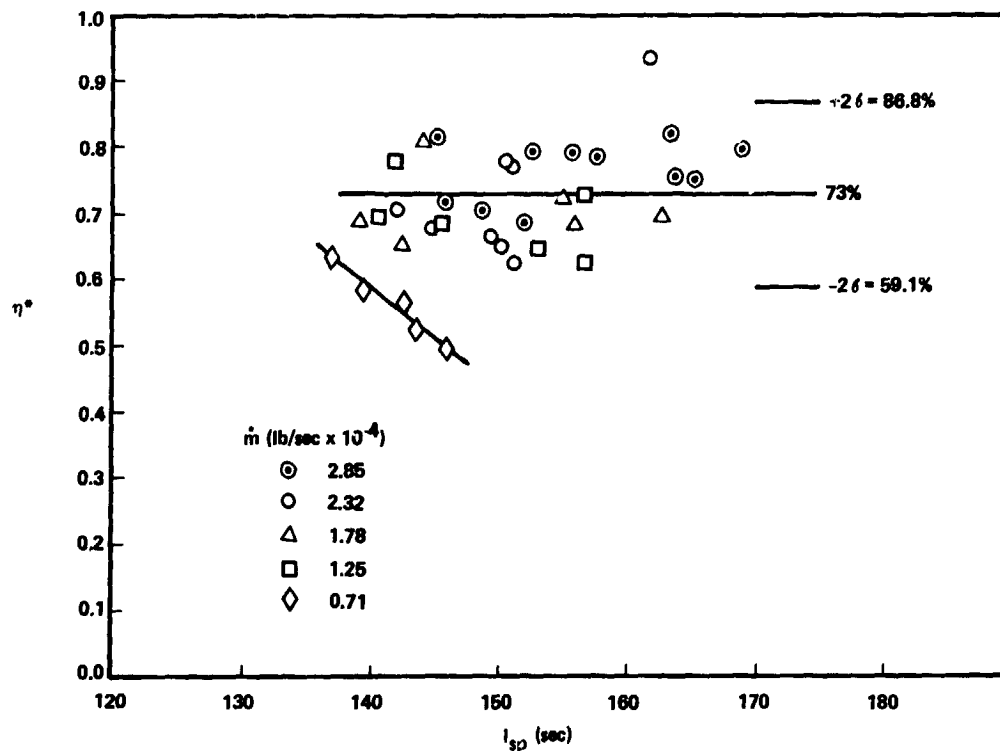


Figure 3. Nitrogen Overall Efficiency

where

η^* = overall efficiency

\dot{m} = propellant mass flow (gm/sec)

h = enthalpy of propellant at inlet conditions (J/gm)

P_{in} = electrical plus chemical power supplied to the thruster

The low flow rate data show a sharp reduction in overall efficiency with increasing specific impulse. This is because of either flow separation, viscous losses in the low-Reynolds-number nozzle (Reference 9) or poor heat transfer in a low-density vortex flow field. The low flow rate data were deliberately omitted from Figure 2 because they were not representative of nitrogen performance. The remaining data indicate 73 percent overall efficiency. The ± 13.9 percent 2σ limits are shown in Figure 3.

Hydrogen performance data are summarized in Figure 4, where specific impulse is shown as a function of power-to-thrust ratio. The solid line in this figure follows the relationship

$$I_{sp} = 294 + 15 (P/F)$$

Overall efficiency as a function of specific impulse is shown in Figure 5 for five different mass flow rates. As previously experienced for nitrogen, the low mass flow rate data show a sharp reduction in overall efficiency with increasing specific impulse. The low flow rate data were deliberately omitted from Figure 4 because they were not representative of hydrogen performance. The remaining data indicate 61 percent overall efficiency. The ± 6.1 percent 2σ limits are shown in Figure 5.

Ammonia performance data are summarized in Figure 6. The solid line in this figure follows the relationship

$$I_{sp} = 110 + 15 (P/F)$$

Overall efficiency for ammonia as a function of specific impulse is shown in Figure 7 for five different mass flow rates. Again, there is a sharp decrease in efficiency at the low mass flow rate with increasing specific impulse. Accordingly, the low flow rate data were omitted from Figure 6. The remaining data indicate 51.5 percent overall efficiency. The ± 8.0 percent 2σ limits are shown in Figure 7. The lower efficiency for ammonia (than for nitrogen or hydrogen) reflects the heat of dissociation required for this propellant.

From the performance data obtained, it is apparent that the flight-qualified HiPEHT demonstrated its adaptability to a variety of propellants. Originally qualified with hot hydrazine decomposition products entering its augmentation heat exchanger, the thruster was operated with cold gas propellant inlet to the heat exchanger. It was run with nitrogen, hydrogen, and ammonia propellants.

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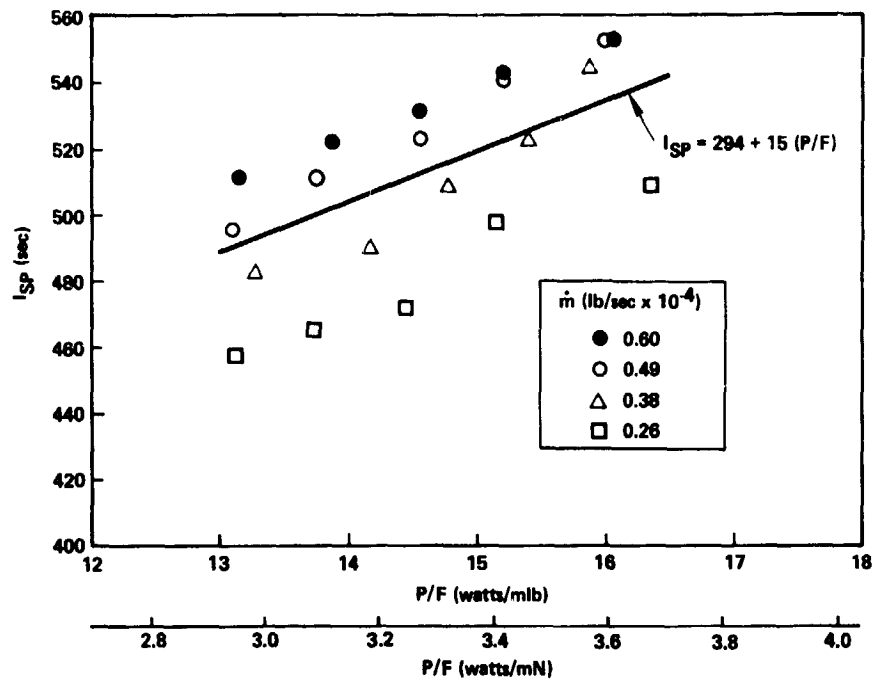


Figure 4. Hydrogen Performance

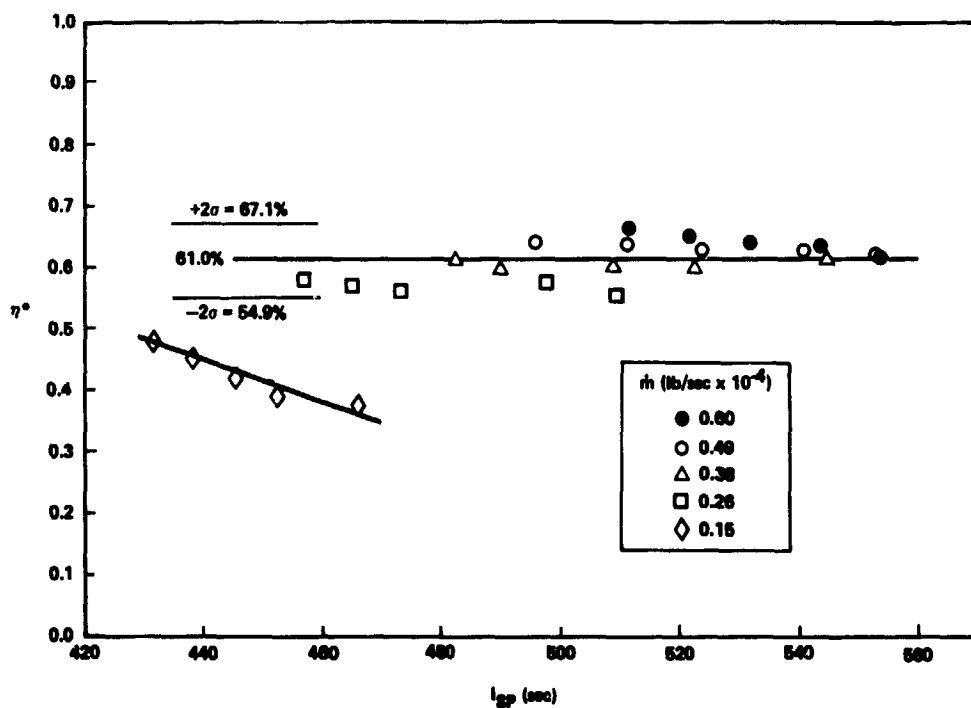


Figure 5. Overall Hydrogen Efficiency

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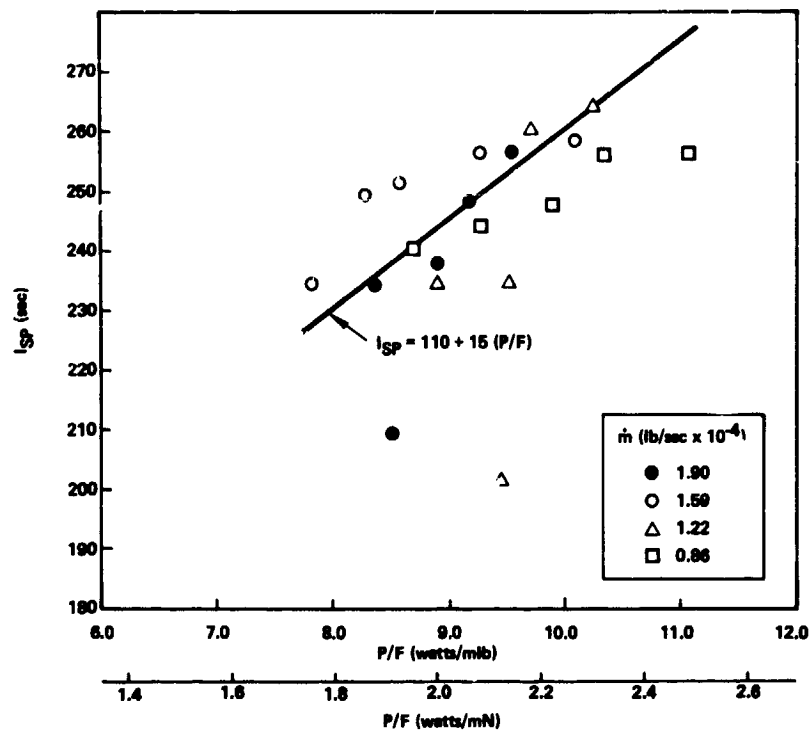


Figure 6. Ammonia Performance

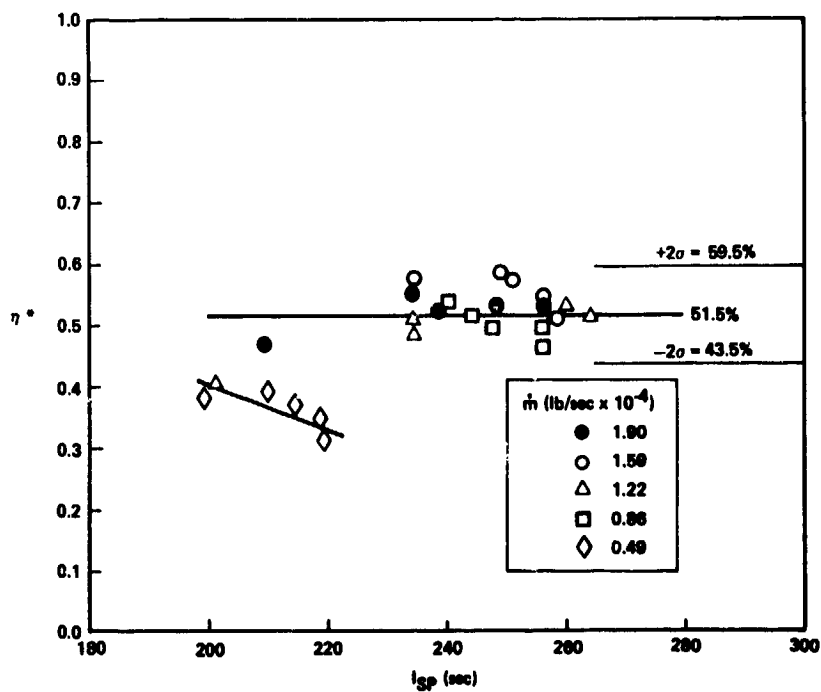


Figure 7. Ammonia Overall Efficiency

The vortex heat exchanger exhibited good overall efficiency with all the propellants employed: hydrazine, nitrogen, hydrogen, and ammonia. Efficiency comparisons with other resistojet thrusters, employing a number of different heating techniques, were made. These comparisons (Tables 1 and 2) showed that the vortex heat exchanger can be efficiently operated with a number of different propellants.

The specific impulse delivered by the vortex heat exchanger will be higher than reported herein when the heat exchanger is operated with hot propellant inlet gases. Conceptual design of a preheater for this purpose is presented in Volume II. At low flow rates, the heat exchanger is not as efficient. At high flow rates, it does not have sufficient heat exchange area, with cold gas inlet, to raise the exhaust gas temperature high enough to deliver specific impulse closer to theoretical limits.

Contamination control is particularly important with immersed high temperature heating elements. Evidence of nitrogen propellant contamination, probably by water vapor, was seen on this project in the form of tungsten oxides which were present on the thruster heating element following the nitrogen test series.

Table 1. Performance Comparison with Other Hydrogen Resistojets

Input Power, kW	0.2	0.5	1.0	3.0	3.0	30.0
Propellant	H ₂	H ₂	H ₂	H ₂	H ₂	H ₂
Heater Configuration	Concentric Tubes	Double Helix	Concentric Contact	Concentric Tubes	Transverse Coils	Concentric Contact
Specific Impulse, sec	670	550	729	840	838	846
Overall Efficiency	0.59	0.61				
Electrical Efficiency	0.69	0.73	0.63	0.88	0.74	0.85
Laboratory	Marquardt	TRW	Giannini	Marquardt	AVCO	Giannini

Sources: References 1, 10, 11 and 12

Table 2. Performance Comparison with Other Ammonia Resistojets

Input Power, kW	0.2	0.5	1.0
Propellant	NH ₃	NH ₃	NH ₃
Heater Configuration	Concentric Tubes	Double Helix	Concentric Contact
Specific Impulse, sec	320	255	423
Overall Efficiency	0.45	0.52	0.50
Electrical Efficiency	0.51	0.57	
Laboratory	Marquardt	TRW	Giannini

Sources: References 1 and 11

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